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DIGITAL TRANSFORMATION IN CONSTRUCTION: A SWOT AND PESTLE ANALYSIS OF INDUSTRY REVOLUTION 4.0 IN MALAYSIA

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Abstract — The construction industry plays a pivotal role in shaping economic growth, environmental sustainability, and societal well-being. It traditionally revolves around three critical dimensions: quality, timeliness, and cost. In the wake of the Fourth Industrial Revolution (IR4.0), the sector is undergoing rapid transformation driven by digital technologies such as robotics, artificial intelligence, and automation. However, the industry's readiness to adopt these innovations remains uneven. This study investigates the current state and future potential of IR4.0 adoption in the construction industry through a structured Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis, complemented by a PESTLE framework to assess the external Opportunities and Threats. The findings are based on a scoping review of 144 peer-reviewed publications from the past five years, ensuring up-to-date insights. Results reveal that IR4.0 technologies have contributed to measurable productivity and efficiency gains globally, with countries such as Germany and China leading implementation efforts. The study emphasises that the effective integration of IR4.0 in the Malaysian construction sector requires coordinated efforts across government, academia, and industry to address systemic challenges and skill gaps. Ultimately, the paper highlights both the transformative potential and the strategic imperatives required to future-proof Malaysia's construction ecosystem in the digital age.

Keywords: digital transformation, industry revolution 4.0, construction industry, SWOT, PESTLE

1.0 INTRODUCTION

Due to the COVID-19 pandemic, the adoption of industrial 4.0 technologies have skyrocketed to a whole new level; thus, the need to understand the trend emerged. The fundamental idea behind Industrial Revolution 4.0 is encapsulated in the emergence of a novel phase characterised by increased digitisation, automation through robotics, and the widespread integration of information and communication technology [1]. In the construction industry, the next revolution crossover into the design and building aspects of the construction is important, as we expect the surroundings and life to be technologically up to date. The first industrial revolution ushered in the construction sector as a result of mechanisation, sowing the seed of the construction of buildings with strong structures in terms of form, frame, and functionality, as new building materials such as glass and iron in the age allowed for the creation of new architectural styles and improved the overall functionality of buildings. These materials enabled the construction of taller, stronger, and more versatile structures, which in turn shaped the urban landscape [2]. The second industrial revolution improved the construction industry by mapping knowledge onto technologies and electricity, enabling the bulk production of cheaper and stronger building materials. The introduction of digital technologies and automation in the construction process led to increased efficiency and productivity [1]. The advent of new prefabrication technology marked the onset of computer-aided design (CAD), which employed electricity and telegraphs during that era. The third industrial revolution ushered in the era of CAD, enabling mass customisation as mechanical and analogue processes transitioned into digital realms on personal computers, facilitated by electronics and information technology. This transformation simplified complex construction by utilising 3D computer-aided design tools, which enabled the premanufacturing of customised building components. Furthermore, the third industrial revolution witnessed the evolution of adaptive repair technologies, exemplified by 3D printing guided by convolutional neural networks. This innovative approach enhances the efficiency and effectiveness of customised and repaired structures [3]. The availability of digital data and online access during the fourth industrial revolution led to the development of the Cyber Physics System (CPS) approach, which aims to integrate technologies for future industrial improvement [4]. Digitalisation has revealed the potential of the construction industry, including automation technologies that utilise robotics and the integration of Building Information Modelling (BIM) with the Internet of Things (IoT), which enhances the flow of the construction process.

Ten key components classify the transformative technologies introduced to the construction sector by IR4.0. These components encompass prefabrication and modular construction, advanced building materials, 3D printing and additive manufacturing, autonomous construction, augmented reality and virtualisation, big data and predictive analytics, wireless monitoring and connected equipment, cloud and real-time collaboration, 3D scanning and photogrammetry, and Building Information Modelling (BIM) [5]. Subsequent sections will provide further elaboration on these components and their practical applications. This study aims to offer a succinct yet comprehensive overview of existing knowledge, referencing pertinent prior and recent research in the field, while outlining the goals and rationale behind the work presented in this submission. This study places particular emphasis on Malaysia's construction sector, where digital adoption is still in its early stages despite national initiatives such as the CIDB Construction 4.0 Strategic Plan (2021–2050). Malaysia serves as a representative case for developing economies navigating the transition toward digitally integrated construction ecosystems. To explore this context, the study employs a dual-framework approach, which is SWOT and PESTLE analyses, to systematically assess internal capabilities and external factors influencing the adoption of IR4.0 technologies. The insights generated form the basis for strategic recommendations presented in the subsequent sections.

1.1. Pre-fabrication and Modular Construction

'Prefabrication' refers to the manufacture of construction elements off-site and assembling them on-site, whereas 'modular construction' refers to prefabrication where the pieces are standardised modules. In the construction industry, modularisation is popular because it can improve project management in terms of time, cost, and efficiency. As technologies improve, prefabricated construction is becoming more common, of greater quality and available in a variety of budgets. Additionally, modular construction addresses the concerns of construction professionals about waste reduction, environmental impact, and life cycle costs [6].

Modular building is one of the world's most high-tech paths of construction system development in terms of energy-saving technologies and cost reduction [7]. Modular construction was previously primarily utilised in low-rise buildings, but as technology advances, it may now be employed in multi-story and even high-rise buildings. Modular construction involves assembling various modular components, including a frame system (such as beams and columns), block containers, necessary facilities, finishing materials, and built-in furniture.

Generalova et al. [7] show that the BROAD Group initially created this innovative technology for quick building construction in China in 2008. Its subsidiary company, Broad Sustainable Building (BSB), established seven sustainable developments in construction technologies, which led to the start of producing modular components at a plant and assembling them only at the construction site. For an example of a building constructed by this corporation, a 30-story hotel known as the "T30 Hotel" in Changsha was constructed in 2012 using only 15 days, and the famous "J57 SkyTown" was constructed in 2015 using only 19 working days. In Europe, reports indicate that prefabricated housing is increasing steadily, and Germany is the largest market, with about 25000 units in 2017 and still growing.

1.2. Advanced Building Materials

Advanced building materials, often synonymous with intelligent building materials, represent a category of innovative substances designed to elevate construction performance, sustainability, and functionality. Extensive research and development efforts have focused on various types of these materials, aiming to enhance different facets of the construction industry. Examples include plant fibre-reinforced composites, phase-change materials (PCMs) in concrete, carbon nanotube (CNT)-reinforced cement-based composites, and building materials derived from Bayer red mud with magnesium cement. Plant fiber-reinforced composites have been explored for their potential to augment the mechanical properties of construction materials and provide a sustainable alternative [8]. Additionally, the incorporation of phase-change materials (PCMs) in concrete holds promise for clean energy storage. Despite potential impacts on mechanical and durability properties, ongoing research focuses on mitigating these challenges. Compensation for the reduction in strength of PCM-containing concrete has been investigated using nanomaterials and supplementary cementitious materials [9].

Carbon nanotubes (CNTs) have been scrutinised for their ability to reinforce cement-based composites and offer outstanding mechanical, electrical, thermal, and chemical properties. The inclusion of CNTs significantly enhances the performance of cement-based materials, with applications ranging from sensing and structural health monitoring to electromagnetic shielding [10]. Furthermore, research has undertaken the preparation of building materials utilising Bayer red mud with magnesium cement, presenting a potentially sustainable solution for construction materials [11]. Interactive building materials are materials that are developed for the ease of humans and require command or external force to perform. It is similar to machines like microwaves, radios, televisions, and others. The IR4.0 concept enhances, smartens, and creates a more sustainable structure with improved performances, long-term maintenance, and refined efficiencies.

1.3. 3D Printing and Additive Manufacturing

In the construction industry, a digital-based system is replacing the current system; additive manufacturing can now be used to build entire buildings as long as the necessary information is provided during the design process. Reduced building costs and time, ease of construction, DIY construction, improved function integration; and reduced waste are all potential advantages of additive manufacturing. It also allows the building to take place in tough or dangerous areas where a human crew would be unsafe. For additive manufacturing in construction, the method used to create the building parts is dependent on the materials used, such as concrete, foam, wax, polymers, and metal. Depending on the materials utilised, binder jetting, directed energy, material extrusion, material jetting, powder bed fusion, sheet lamination, and vat photopolymerisation are some of the processes used. The project's quality, cost, timeline, and productivity are affected by the complexity of each of the seven processing steps.

For instance, Khajavi et al. [12] conducted a comparative analysis between 3D concrete printing and traditional methods, evaluating their competitiveness in terms of cost and time. Their findings underscored the notable competitiveness of 3D concrete printing. Shakor et al. [13] explored the potential of 3D printing using binder jetting in construction, highlighting the most suitable materials for this technology. Additionally, a novel approach to large-scale additive manufacturing in construction introduces the use of a tower crane-based 3D printing system controlled by artificial intelligence (AI). This innovative concept addresses a key limitation of additive manufacturing in construction—the build volume—by leveraging the primary machine in the field: tower cranes. Parisi et al. [14] introduced the concept of a tower crane-based 3D printing system controlled by deep reinforcement learning and evaluated its feasibility by examining the accuracy achieved in the printing process. On December 14, 2016, Spain witnessed the construction of the world's first 3D-printed pedestrian bridge, which represents an important turning point in additive manufacturing [15].

1.4. Autonomous Construction

Construction tasks are characterised by their repetitive, time-sensitive, physically demanding, and precision-oriented nature, which makes them well-suited for the application of autonomous machinery. Robotics, with their ability to operate faster and more precisely than humans, offer an ideal means of enhancing productivity, as they do not experience fatigue. Additionally, the implementation of robotic automation in construction can mitigate risks associated with hazardous tasks, consequently reducing the injury rate. This involves introducing autonomous behaviour at the basic task level for on-site construction robots, focusing on algorithms for mobile robot navigation and relative pose estimation [16].

A fully autonomous construction system is envisioned to operate without supervision or assistance, equipped with artificial intelligence to respond and adapt to unpredictably changing task conditions. However, the inherent risks in construction, where errors can lead to fatal incidents, coupled with the ongoing maturation of technology, currently restrict the deployment of perfect autonomous systems. As a result, the existing automation in the construction industry predominantly involves semi-autonomous robots that operate under human supervision. For instance, the Bots2ReC project developed a robotic system for the semi-autonomous removal of asbestos in apartment buildings. In this scenario, mobile manipulators perform tasks such as plaster and tile removal as part of the semi-autonomous construction process, integrated into the overall construction workflow [17].

Furthermore, within the realm of lunar exploration, a semi-autonomous teleoperation framework has been proposed for robotic missions aimed at establishing infrastructure and preparing for the sustained presence of humans on the Moon. This framework enables remote human operators to tele-control multiple cooperative robots, facilitating tasks such as the construction of human habitats and the assembly of solar photovoltaic panels [18]. The potential of semi-autonomous robots extends to addressing specific challenges within the construction industry, spanning hazardous tasks like asbestos removal to the establishment of infrastructure for lunar exploration.

1.5. Augmented Reality and Visualization

In the construction industry, the idea of using virtual reality (VR) for visualisation and the awareness of the real environment in augmented reality (AR) provides information that helps in performing real-world tasks. Rankohi and Waugh's [19] studies indicate that the construction team have a high interest in using AR technologies to monitor the progress and detect any defective works. The use of AR and VR will accelerate the construction process by simplifying supervision, coordination, positioning, inspection, and many other tasks.

For example, AR can be used to overlay digital models on the physical environment, allowing users to visualise and interact with building designs in real time. This technology can improve communication and collaboration among stakeholders, reduce errors, and enhance decision-making [20]. Furthermore, AR can be used to overlay digital information onto physical equipment, providing workers with real-time guidance and instructions for maintenance and repair tasks. This technology can improve efficiency, reduce errors, and minimise downtime [21]. Aside from that, VR can be used to simulate hazardous scenarios and provide workers with a safe environment to practice safety procedures. This technology can improve safety training effectiveness, reduce accidents, and minimise downtime [22]. VR can also be used to create immersive and interactive environments for design reviews, allowing stakeholders to visualise and evaluate building designs more realistically and engagingly. This technology can improve communication, collaboration, and decision-making [23]. These technologies have the chance to change the construction industry by improving efficiency, reducing errors, enhancing safety, and enabling more effective decision-making.

1.6. Big Data and Predictive Analytics

In the construction industry, the term "Big Data" refers to vast sets of information amassed and archived over time, continually expanding with additional data inputs each day, mirroring trends seen in other sectors. The construction industry is increasingly leveraging Big Data tools for predictive analysis to enhance decision-making and risk management. A notable study published in 2020 advocated for the application of natural language processing (NLP) and text mining of big data to scrutinise engineering documents, leading to the development of tools for forecasting and risk management in the engineering procurement and construction (EPC) sector [24]. This study formulated five decision support system modules, encompassing engineering design cost prediction, engineering design error analysis, and engineering design change analysis. These modules were designed to forecast man-hours, analyse design errors, and predict change orders, respectively. In the context of construction processes, Big Data contributes by offering insights for optimising the sequencing of construction activities, considering factors like traffic, weather, and equipment utilisation. During operations, data collected from embedded sensors provides real-time information about the performance of buildings, bridges, or any construction, enabling effective monitoring.

The construction industry leverages Big Data in various applications, such as the Collaborative Construction Industry Integrated Management Service System Framework—an extensive system firmly rooted in Big Data. This framework focuses on delivering intelligent decision-making services throughout the entire construction process and encompasses collaborative design management, building supply chain management, project collaborative management, and hardcover personalisation [25]. Additionally, the Engineering Machine-Learning Automation Platform (EMAP), a cloud-based integrated analysis tool, uses Big Data and AI/ML technology to forecast contractor risks and facilitate decision-making at each stage of Engineering Procurement and Construction (EPC) projects. Comprising five modules—Invitation to Bid (ITB) Analysis, Design Cost Estimation, Design Error Checking, Change Order Forecasting, and Equipment Predictive Maintenance—EMAP harnesses advanced AI/ML algorithms [26].

1.7. Wireless Monitoring and Connected Equipment

IR4.0 connects machines and humans via the Internet of Things (IoT) [27]. The world is becoming more connected with the use of smart technologies; thus, in the construction industry, the use of sensors and devices for monitoring is essential. The use of wireless sensor networks in the construction industry is mainly for monitoring and safety purposes. Building sites are complex, and the movement and interaction of people and products during construction activities make safety management difficult. Injuries in the construction industry are always high and even had the highest rate of death in 2010. Additionally, the working environment negatively impacts the health and lifestyle of workers, leading to long-term health problems. Working in poor conditions eventually slows down the process and may trigger accidents.

For construction activities, wireless sensor networks develop a wearable sensor device for workers. These gadgets can monitor workers' physiological conditions and even detect their stride patterns to detect fall dangers in the workplace. By ensuring the workers wear the sensor, monitoring to keep track of the health of all the workers is possible. After sensing the dangerous gait pattern, an alert is triggered to warn the respective worker and prevent accidents. For construction sites, there are other sensors that can monitor the properties of concrete during curing or even track environmental conditions. Smart structures involve the use of sensors to monitor specified conditions and detect any construction faults. Examples of use of the sensors are alerting the owner during fire or extreme gas emissions or monitoring the living conditions inside the house even far away [28]. Besides these, the wireless sensor network allows the interaction between machines and humans over the internet to become simpler and easier.

1.8. Cloud and Real-Time Collaboration

In the construction industry, construction teams such as stakeholders, contractors, subcontractors, surveyors, consultants, and parties involved had difficulties attending meetings unless scheduled a long time beforehand. Miscommunication can cause construction errors and delays. As a result, the Service-Orientated Architecture (SOA) that supports cloud computing technologies arose, allowing enterprises to share their IT infrastructure [29].

Cloud computing has five characteristics, one of which is that users can connect to the network at any time and from any location [30]. The second element is the shared pool feature, which refers to a multi-tenancy infrastructure that allows several users to access and use the same resource at the same time. The third feature is the elasticity, which allows the user to change their request for computer resources on the go. The fourth attribute is the on-demand self-service aspect of cloud computing, which is accessible to everyone without the requirement for cloud provider services. Finally, the fifth characteristic is the pay-as-you-go characteristic, which means that users only pay for cloud services that they use.

1.9 3D Scanning and Photogrammetry

The construction industry is increasingly using two 3D scanning technologies: photogrammetry and laser scanning. For the construction industry, scanning technologies can be applied to all types of projects for real-time monitoring to determine the progress of construction projects. These scanning technologies can easily measure the dimensions of a geometry or structure, potentially replacing the old surveying techniques that required more time to obtain accurate data. Besides that, these technologies do not involve humans in the process; thus, manual errors are excluded.

3D scanning and photogrammetry possess diverse applications globally. For instance, Kiriiak [31] assessed 3D scanning methods for digital support in the development of nuclear power plants. In the case study of Tangwei village in China, multi-view image photogrammetry was employed. Safa et al. [32] introduced an integrated quality management system for piping fabrication, leveraging 3D laser scanning and photogrammetry to enhance quality control processes in the construction sector. Furthermore, photogrammetry proves valuable in tasks such as reconstructing historical buildings, statues, and sculptures, as well as contributing to the development of new projects [33].

1.10 Building Information Modelling (BIM)

BIM has made a major contribution to the construction industry; it has the potential to achieve the objectives of decreasing project cost and time as well as increasing the productivity and quality of the project. BIM stimulates a

3D model known as a building information model that contains accurate data and information for supporting the design, fabrication, and construction activities of the project. Studies by Dikbas & Scherer [34] demonstrated that the building information model can illustrate the entire building life cycle. Different countries across the world have already reported to comply with the BIM method in a few years [35].

For example, during the construction of high-rise structures, BIM is used to estimate vertical transportation demands [36]. The use of temporary vertical transportation systems, such as tower cranes, temporary elevators, and concrete pumps, results in a high project cost. With BIM estimates, precise vertical transportation demand estimation is required to determine the temporary vertical transportation system required. Vignali et al. [37] conducted a study on the use of BIM for existing road infrastructure. The research entails the creation of a new road segment as well as its link to the current road network. China promotes BIM as the vital key to the informatisation of the Architecture, Engineering and Construction (AEC) industry and mentions the critical demand of professionals in BIM for the evolution of education in the building industry [38].

IR4.0 brought advanced technologies to the construction industry, which led to the digitalised construction era. The application of these technologies has significant potential to address current issues in the construction industry, including low productivity, high project costs, high fatality rates, excessive waste production, and an oversupply of residential houses. These benefits are clear because they enhance operational performance, which has encouraged and advanced the industry's revolution. However, there will always be the risks and difficulties of applying new technologies. The complexity of construction projects, which involve many stakeholders, some of whom may oppose the application, makes it hard to use these technologies. This indicated that not everyone had the readiness and acceptance to adopt the IR4.0 technologies. The pursuit of these technologies may require internal changes throughout the company, and large companies won't spend on them, which leaves only small and medium enterprises (SMEs) to adopt them [39].

Besides that, the lack of skills is the major difficulty in digital transformation [39]. Since these technologies are new and still evolving, the findings, training, and re-skilling of professionals represent only a small portion of what is needed. Those who lack skills in these technologies will find using new digital tools and applications difficult. Adopting these IR4.0 technologies involves high upfront costs, pushing the difficulties to a higher level.

Industry 4.0 has introduced a range of innovative tools and techniques to the construction industry, including drones, prefabrication, wireless sensor networks, automation, Building Information Modelling (BIM), artificial intelligence, and more. This study explores the integration of these technologies and examines their impact on current practices as well as future trends within the construction sector.

2.0 METHODS

This research study was carried out by accessing historical research journals and articles through online resources. Several information websites were surfed through for collecting data and information needed for this research study. Online resource websites such as Google Scholar, ScienceDirect, Scopus, Web of Science and Research Gate were used for data and information gathering. Board search terms were initially used and resulted in a large list of research. Thus, a scoping review was done to obtain a narrower and more accurate search result. Keywords for search terms consist of Industrial Revolution 4.0, Industry 4.0, Building Information Modelling and nine other IR4.0 technologies. Additionally, Boolean operators were employed to combine the exploration keywords with those related to the construction industry for further searches. Due to the popularity of IR4.0, an excessive number of results were generated; therefore, a focus was placed on articles from the last five years. The screening was applied to the search results to eliminate duplicated articles obtained from different websites and remove those that did not explicitly relate to the construction industry. During the process, a total of 144 articles and journals were reviewed up to the introduction section, and 46 publications were selected to generate the search results.

In Malaysia, the Construction Industry Development Board has introduced the Construction 4.0 Strategic Plan (2021–2025), aimed at accelerating digital transformation across the construction sector. Chan et al. [52] introduce the Kaleidoscope Model, a strategic roadmap for evaluating the effectiveness of Construction 4.0 policy implementation in Malaysia. Their study, based on document analysis and stakeholder interviews, finds that policy adoption and implementation are the primary drivers influencing sectoral uptake, while implementation challenges do not significantly moderate policy impact. This framework provides a critical lens for understanding the alignment between national policy ambition and actual industry transformation. To systematically assess internal and external factors affecting IR4.0 adoption, this study employs a dual analytical framework combining SWOT and PESTLE methodologies.

A SWOT analysis was performed to analyse the application of IR4.0 in the construction industry. SWOT analysis is a technique capable of assessing the internal and external factors as well as the future potential. The internal factors refer to strengths (S) and weaknesses (W) and they are the internal attributes and resources that provide advantages or disadvantages over others. ‘Strengths’ support and ‘weaknesses’ work against a successful outcome. In this study, ‘Strengths’ and ‘Weaknesses’ will refer to the factors for implementing IR4.0 in the construction industry. PESTLE analysis is a framework or tool to analyse factors that have an impact on and influence project performance. These analytical tools offer expert commentary on the situation and provide a clear understanding of the external factors. The term ‘political’ refers to the requirements of government authorities for various activities and the degree to which government policy may have an impact. ‘Economic’ is the overall economic performance that could drastically affect the applicability of the project. The next factor is ‘Social,’ which examines the social environment and emerging trends within the population. The ‘Technological’ factors pertain to innovations in technology and the level of technological awareness within an industry. ‘Legal’ refers to the laws and regulations that affect the industry, as well as the need to stay informed about any changes. Lastly, the term ‘environmental’ refers to factors that include ecological influences and aspects of the environment, such as the impact of climate change on the industry. The PESTLE analysis will be incorporated within the Threats (T) and Opportunities (O) sections of the SWOT analysis.

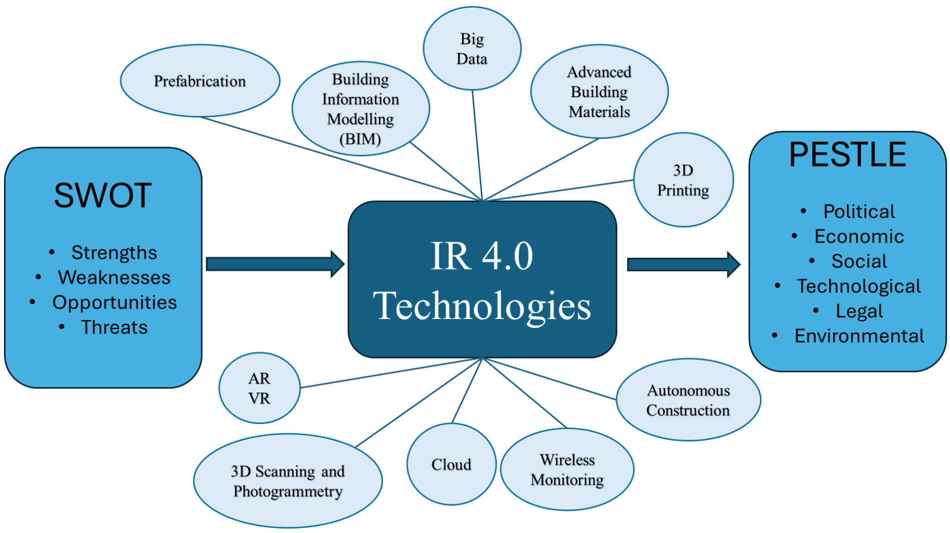

Figure 1 Conceptual Diagram Linking IR4.0 Technologies to SWOT and PESTLE Dimensions.

Figure 1 illustrates the conceptual framework adopted in this study, linking Industry 4.0 (IR4.0) technologies to SWOT and PESTLE analytical dimensions. At the centre of the framework are ten key IR4.0 technologies identified in the literature: prefabrication, building information modelling (BIM), big data, advanced building materials, 3D printing, autonomous construction, wireless monitoring, cloud collaboration, 3D scanning and photogrammetry, and AR/VR. These technologies were selected based on their relevance and transformative impact within the construction industry, particularly in the Malaysian context. The diagram shows that SWOT analysis was used to evaluate the internal strategic environments, such as strengths, weaknesses, opportunities, and threats, which are associated with the adoption of these technologies. Simultaneously, PESTLE analysis was employed to assess the external macro-environmental factors, which are political, economic, social, technological, legal, and environmental, that shape opportunities and threats within the SWOT framework. This integrative approach enables a comprehensive assessment of both internal capabilities and external pressures, supporting a strategic understanding of digital transformation in the construction sector.

3.0 RESULTS AND DISCUSSION

3.1. Adoption of IR4.0 Elements Worldwide

The construction industry has historically lagged other sectors in terms of productivity. However, the advent of the Fourth Industrial Revolution (IR4.0) presents a significant opportunity to drive improvements and modernise construction practices. Although there were waves of adoption for some of these elements, the technologies were not mature enough at the time, leading to their neglect. For instance, the concept of modular construction was introduced in Germany as early as 1916 with the "Hausbaufabrik" idea, as documented by Jones [40]. The Torten Estate, comprising 314 cube-shaped terraced houses, demonstrated the practical application of modular construction. However, construction flaws identified during occupancy led many residents to undertake corrective repairs. Historically, the perception of prefabrication and modular construction leaned toward negativity, often attributing issues to poor craftsmanship. However, recent advancements in technology and craftsmanship have transformed this perspective, enabling more sophisticated designs and the use of superior materials. In the past, architects and engineers relied on 2D technical drawings, either hand-drawn or created through computer-aided design, to develop components and oversee project development. This approach led to various challenges, often only identified after prefabricated components or modules were transported to the installation site. Detecting errors late in the construction process could cause significant delays and increased expenses, as adjustments or the production of new items might be necessary. Such issues have ripple effects on the entire construction timeline.

In the present day, modular building is experiencing renewed interest and increased investment, and several factors suggest that it may establish itself as a lasting trend. The advent of digital tools has significantly transformed the landscape of modular construction. Building Information Modelling (BIM) is now employed alongside various construction methods to verify the seamless fit of prefabricated components or modules during installation on the construction site (refer to the 3D Infrastructure Modelling and BIM use case). BIM allows for the virtual construction of a project before its physical realisation, mitigating many challenges and inefficiencies that may arise during the construction process. This technology brings new life to prefabrication and modular construction by enabling more complex designs, improving communication and teamwork among everyone involved, and ensuring that high-quality buildings are made. Consumer perceptions of prefab homes are gradually shifting, particularly as novel and diverse material options enhance the visual appeal of prefab structures.

The incorporation and utilisation of advanced building materials have significantly contributed to the evolution of the construction sector during the Industrial Revolution, presenting more viable alternatives to cutting-edge construction practices. Noteworthy examples of such materials include modular bamboo in the Philippines, the Cabkoma Strand Rod in Japan, and the widely adopted light-generating self-healing concrete in Japan. Market data indicate a remarkable surge in demand for these advanced building materials over time. For instance, the introduction of aluminium foam has paved the way for 3D printing in construction. 3D printing (3DP) stands as a revolutionary advancement in civil engineering, adding automation and providing design, sustainability, and efficiency benefits. Construction 3D printing has the potential to expedite and precisely fabricate intricate or customised structures, leading to reduced labour costs and minimised waste production. Additionally, it opens possibilities for construction in challenging or hazardous locations where human labour might be impractical, such as in space. A significant milestone in this realm occurred on December 14, 2016, with the inauguration of the world's first 3D-printed pedestrian bridge (3DBRIDGE) in the urban park of Castilla-La Mancha in Alcobendas, Madrid, Spain [15]. ACCIONA, responsible for structural design, material development, and 3D-printed piece manufacturing, introduced the 3DBUILD technology. This 12-meter-long and 1.75-meter-wide bridge, printed in micro-reinforced concrete, marked a groundbreaking achievement. Notably, companies like WinSun Decoration Design Engineering in Shanghai are utilising massive 3D printers to spray a mixture of quick-drying cement and recyclable raw materials to produce blocks off-site [41]. These blocks are then assembled on the construction site, showcasing a potential future application for constructing larger residences or even skyscrapers. The adaptability of 3D printing in the construction sector extends to generating individual components or 'printing' entire buildings, leveraging the industry's familiarity with computer-aided manufacturing, where much of the required information is generated during the design process.

Automated technology has the potential to enhance the efficiency of repetitive processes inherent in prefabrication and modular construction. Autonomous machinery, such as robots and cranes, can execute tasks with precision, consistency, and reliability, whether stationed in specialised facilities offsite or on the construction site itself. The use of these machines has the dual advantage of reducing the time required for task completion and minimising the risk of damage to building components and other equipment. Furthermore, it contributes to the safety of workers by keeping them away from potentially hazardous activities, ultimately augmenting the overall capacity of the facility and resulting in cost savings. The integration of artificial intelligence (AI) is increasingly applied to undertake more intricate tasks. The synergy between these construction approaches and effective modelling tools has the potential to decrease expenses associated with design flaws and communication gaps. This integration can also lead to reductions in material waste, labour costs, rework expenses, and overall scheduling improvements that prevent clashes or unforeseen complications. A notable example is Bouygues Construction, a French company that employs an autonomous rover named EffiBOT. This innovative rover, initially designed for the logistics industry, adeptly follows construction workers on the job site, efficiently transporting equipment and goods, with a capacity of handling up to 300 kg [42].

Sensors play a critical role in enabling automation within the construction industry. These devices can capture real-time data such as location, temperature, pressure, and other environmental parameters. Construction organisations can leverage sensor technologies to automate a wide range of equipment and robotic systems, according to operational needs. Sensors can transmit signals that trigger specific machine functions, facilitating precise and responsive automation. For instance, they are commonly employed in welding and fabrication processes to enhance accuracy and efficiency. Additionally, sensors allow builders to virtually navigate a building's internal systems, such as piping networks, to assess spatial constraints for maintenance and repairs, thereby reducing the need for invasive inspections. Virtual reality emerges as a substantial form of automation in this context, employing meticulously programmed 3D scans that exhibit high accuracy and are immune to human errors. In China, for example, virtual reality (VR) has been identified as an optimal method for simulating crane lifts in a virtual environment, involving planners in the process [43]. Planners may realistically assemble construction pieces in the VR environment through object manipulation and interaction, which has tremendous potential usefulness in complex project planning and prefabrication. Besides VR, another element of the industry revolution 4.0 in the construction sector is wireless monitoring and connected equipment. Engineers and contractors are increasingly recognising the advantages of incorporating smart sensors inside buildings. Various sensors and devices are being developed for diverse purposes on construction sites. Some are specifically designed for monitoring concrete characteristics during the curing process, while others focus on tracking environmental factors or project equipment. By overseeing concrete attributes such as temperature, strength, maturity, moisture content, pH, and relative humidity (RH), sensors play a crucial role in enhancing project schedules and ensuring safety and durability. These sensors are employed throughout the initial stages of construction, encompassing concrete mixing, placement, and curing, thereby optimising essential operations and improving overall process efficiency. Key aspects addressed during the construction process include maintaining appropriate moisture content during mixing and removing formwork and post-tensioning, as these factors significantly impact the performance and condition of the concrete, which are vital for the structure's safety and longevity. In China, the continuous monitoring of a building's state through wireless sensor networks enhances its safety. This is because the information gleaned from building monitoring can be utilised to assess the level of attrition of the structure's materials, averting further serious damage. A wireless sensor network can warn an engineer of a building's seismic resistance, and in this instance, various precautionary steps can be implemented.

Big data is another element in the Industrial Revolution 4.0 in the construction sector that is trending now. Big data is often used to perform predictive analytics. Several countries have already adopted this technology for risk analysis, predictive analytics, and warranty analysis as part of project optimisation. The building business is not immune to the widespread digital transformation. Throughout a facility's life cycle, the industry grapples with a plethora of data spanning various disciplines. The objective of Building Information Modelling (BIM) is to systematically compile multi-dimensional CAD data, fostering collaborative efforts across multiple disciplines among stakeholders. The recent surge in building information modelling (BIM) adoption has the potential to democratise access to 3D printing. A comprehensive market report on BIM's usage in the AEC industry, along with projections for 2009, was published by Young Jr et al. [44], drawing insights from a questionnaire survey completed by 82 architects, 101 engineers, 80 contractors, and 39 owners, constituting a total sample size of 302 individuals in the United States. The survey revealed architects as the most frequent users of BIM, with 43% incorporating it in more than 60% of their projects. In contrast, contractors demonstrated the least frequent usage, with almost half (45%) implementing it on less than 15% of projects, and only a quarter (23%) applying it to more than 60% of their projects.

Several companies in Georgia embraced BIM and underwent analysis. The Aquarium Hilton Garden Inn project, encompassing a mixed-use hotel, retail shops, and a parking deck, initially lacked BIM incorporation in its design.

However, the general contractor spearheaded the project team in developing architectural, structural, mechanical, electrical, and plumbing models during the design development phase. By utilising BIM technology, the general contractor successfully identified potential collisions, or clashes, between different structural and mechanical systems. At Savannah State University, BIM is used for alternative analysis (value analysis) in the project planning phase to pinpoint the most cost-effective and practical building layout. Through a series of collaborative 3D viewing sessions, the owner was able to review all virtual models and select the one that best suited their needs. These collaborative viewing sessions not only facilitated enhanced stakeholder communication and trust but also enabled prompt decision-making early in the process [45].

Khudzari, Radzi, & Rahman [49] conducted a systematic literature review focused on emerging technologies in the Malaysian construction industry, finding limited local research on key tools emphasised in the national Construction 4.0 Strategic Plan, such as 3D printing, autonomous construction, photogrammetry, and big data analytics. This gap underscores the disconnect between policy aspirations and academic attention in Malaysia's construction ecosystem. Research indicates that the global construction sector has adopted these elements. Those countries had started to adopt the elements that fit perfectly, encountering their difficulties and problems, such as modular construction, which fights well against the high demand for housing as the population there is high. Additionally, China, having adopted most of the elements, currently plays a crucial role in the construction sector. The results showed that IR4.0 is the upcoming trend that will bring the construction industry a large step forward in productivity and quality, yielding a new revolution. Table 1 presents a synthesis of global case studies highlighting the adoption of various IR4.0 technologies within the construction sector. These examples, drawn from a review of 144 peer-reviewed publications, illustrate in what way different countries have implemented technologies such as modular construction, 3D printing, and Building Information Modelling (BIM). The case studies reveal differing levels of technological maturity, with countries such as China, Germany, and Japan emerging as leaders in digital construction innovation. These international insights provide a comparative baseline to contextualise Malaysia's current progress in adopting IR4.0 technologies. Advanced economies drive much of the global momentum, but Malaysia is gradually enhancing its digital capabilities through national strategies and pilot initiatives. Programmes such as the Construction Industry Transformation Programme (CITP) and CIDB's digital roadmap promote the integration of BIM and modular systems in public sector projects. Nonetheless, limited adoption among small and medium-sized enterprises (SMEs) and persistent skill gaps remain critical barriers. Malaysia's situation reflects a transitional phase, characterised by robust policy frameworks but inconsistent implementation at the operational level.

Table 1 Review outcomes from the countries that applied IR4.0 elements.

Element	**Country**
Pre-fabrication and Modular Construction	Germany- Hausbaufabrik Japan- Nakagin Capsule Tower China-T30 Hotel, J57 SkyTown
Advanced Building Materials	Philippines – modular bamboo; Japan – Cabkoma Strand Rod and light-generating self-healing concrete
3D Printing and Additive Manufacturing	China, Spain - 3DBRIDGE
Autonomous Construction	French - EffiBOT
Augmented Reality and Visualization	China, Canada
Big Data and Predictive Analytics	Germany, China, Australia
Wireless Monitoring and Connected Equipment	United States, Belgium
Cloud and Real-Time Collaboration	China
3D Scanning and Photogrammetry	China, England, Canada
Building Information Modelling	Japan, China, England, Germany, Georgia

3.2 Strength (S) and Weakness (W) of Adoption IR4.0 in the Construction Sector

The adoption of IR4.0 in the construction industry highly improves the productivity of a project. Each of the elements under IR4.0 in construction had its own strengths and weaknesses; thus, their application was chosen based on the project itself. For instance, the application of modular construction is done to counter the real estate demand and the availability and cost of qualified construction labour, especially in countries with high-density populations in areas such as India and Hong Kong. Contemporary construction approaches predominantly revolve around manufacturing components in factories, offering potential advantages such as accelerated construction, diminished housing defects, and decreased energy and waste consumption. These aspects can mitigate both construction waste and safety risks in the construction process.

The industry is incorporating new, lightweight materials and digital technologies to enhance design capabilities, increase manufacturing precision and productivity, and streamline logistics. Certain builders are emphasising sustainability, aesthetics, and the upscale segment of the market to counter the historical perception that prefabricated housing is an unappealing, budget-oriented, and lower-quality option. New entrants and first movers who aren't ready to put up with the industry's fragmentation and low productivity are disrupting the market and changing incumbents' mindsets. The benefits of employing advanced building materials include fewer demands on the construction site's facilities and equipment, a safer working environment when building components are created off-site, and lower labour expenses. Standardisation, modularisation, and prefabrication have the potential to significantly boost construction productivity. The standardisation of work has various advantages, including cost savings, fewer interface and tolerance issues, and greater predictability of outputs. Modularisation adds to the advantages of standardisation by allowing more customisation and flexibility. There are fewer design flaws. The fabrication of construction components is of a higher grade. Quality control is easy to achieve in the plant. Initiating the reduction of carbon footprints in construction materials can begin in the manufacturing phase by employing energy-efficient processes and utilising discarded or recycled materials. Moreover, additional materials may contribute to addressing emerging challenges related to long-term durability in a changing climate.

BIM, equipped with its diverse digital tools and processes, holds significant potential for enhancing the operability of the construction industry. The advent of IR4.0 introduces numerous possibilities for progress, setting a new standard for what can be achieved with digital data. The integration of BIM early in a project unlocks the benefits of digital data, contributing to readiness for the industrialisation of construction. BIM technology incorporates time, cost, and sustainability considerations into a 6D model, enriching the selection and application of completed components through three-dimensional visualisations. This not only ensures quality and timeliness but also eliminates waste and elevates overall project performance. During the construction phase, the collaboration between BIM technology and Augmented Reality (AR) facilitates the translation of digital data into physical components. The synergistic use of BIM technology and digital processing fosters well-organised construction, intelligent management, and precise data distribution. Manufacturers of prefabricated components can enhance the integration of design, fabrication, construction, and maintenance processes through BIM technology, providing accurate and pertinent information. In the construction process, the information within the BIM simulation effectively reduces the demand for prefabricated elements. Stakeholders in construction must adeptly manage the resulting influx of data. Effectively processing and leveraging this data enables stakeholders to unlock the full potential of this transformation, leading to new business opportunities in a digital world.

Leveraging big data and analytics, processes generate fresh insights from the vast data reservoirs accumulated throughout the planning, construction, and operational phases of the current facility. Innovative simulation and virtual reality methods are under development to identify interdependencies and clashes, enabling a virtual simulation of the facility before its actual construction. Real-time engagement and communication with stakeholders are facilitated, and on-site workers can receive additional instructions and information, thanks to advancements in mobile connectivity and augmented reality. Drones equipped with embedded sensors can swiftly detect any irregularities in the construction process and facilitate deformation monitoring. Simultaneously, all collected data is transmitted in real-time to the cloud, providing all stakeholders with access to necessary corrective actions. Contractors can employ data analytics and supporting technology in the construction sector to mitigate risks, enhance project management, and optimise costs and timelines.

On the other side, there are always factors that prevent the application of IR4.0 in the construction industry. For modular construction, the weakness will be that the cost of prefabrication products will be higher as well as the initial costs of setting up the production line for manufacturing components. Modules are currently transported by massive trucks on roadways from manufacturing facilities to construction sites. This leads to carbon emissions in the environment, as well as traffic congestion and difficulty moving across the road network due to slow-moving automobiles. This would result in even more emissions from other vehicles on the road. It is crucial to consider that expenses associated with technical equipment training can accumulate rapidly. This training may involve hiring an external consultant to instruct the current workforce, leading to a substantial investment of time and resources. If concerns about job cuts or redundancy arise, trainees may be reluctant to embrace such technology. The conclusions indicate that this uncertainty could hinder the adoption of emerging technology, giving rise to populism and constraining workers' adaptability to new technological advancements. Once again, technology is perceived as a means of mitigating economic and organisational risks, of which businesses aim to steer clear.

High requirements and a lack of knowledge of handling IR4.0 technologies are the barriers that prevent the implementation of IR4.0 in the construction sector. Proficiency in handling or using new IR4.0 technologies is essential for adaptation and advancement. Employee recruitment and training, as well as the learning of integration skills, are all required as part of the implementation of IR4 technology. In the United States, for example, Amazon has manufacturing machine-only delivery centres, decreasing the need for professional warehouse staff. While it may seem like a cost-effective choice, it necessitates skilled operators and maintenance personnel. According to Neugebauer [47], the adoption of IR4.0 technology can influence how production and operations are conducted. As a result, workplace culture, management structure, and productivity may all suffer. Although many seasoned businesspeople are ready to embrace new technologies, others may be apprehensive due to a lack of expertise or a desire to learn new approaches. As indicated by the aforementioned hurdles, construction organisations are reticent to incorporate new technologies into their operations. A firm's incorporation of IR4.0 technology does not guarantee continuous improvement, particularly if it lacks close monitoring. When planning a project, long-term outcomes and risk analyses should be considered. In an ideal world, a team would be assigned to oversee not only the entire deployment process but also its continuing use after the rollout phase has ended. Until the technology is developed, users should expect a venue to express their issues and queries. Users should be able to seek help right away if they need it; otherwise, they will be unwilling to learn and embrace the technology.

Sector 4.0 has far-reaching repercussions for the construction industry as a whole, the companies involved, the environment, and the general public. In addition to the financial benefits of increased productivity, efficiency, quality, and cooperation, its application can assist in enhancing safety, sustainability, and decision-making, as well as the construction industry's negative image over time. Despite the benefits, all stakeholders involved must overcome some hurdles to achieve a successful deployment. Various hurdles must be accepted to facilitate the transition to Industry Revolution 4.0. To obtain a nationwide and worldwide competitive advantage, businesses should prioritise Industry Revolution 4.0 in their strategic plans. Table 2 summarises the strengths and weaknesses of adopting IR-4.0 in the construction sector.

Table 2 consolidates the internal factors, which are strengths and weaknesses, affecting IR4.0 adoption in the construction sector. These factors were derived from the literature review and synthesised to highlight the dual nature of digital transformation, showcasing both the efficiency and productivity benefits as well as the barriers, such as high costs, skill gaps, and organisational resistance. The table supports the SWOT framework's internal analysis and underlines the reason strategic readiness is vital for effective implementation.

Table 2 Summary of strength and weaknesses of adoption IR4.0 in the construction sector

Strength	**Weakness**
Enhance project productivity	Initial costs of prefabrication products and setting up production lines are high, impacting affordability.
Each IR4.0 element offers unique strengths, allowing for tailored application based on project requirements.	Transporting modules via trucks contributes to carbon emissions, traffic congestion, and environmental degradation.
Modular construction counters real estate demands and addresses issues related to qualified construction workers, especially in densely populated areas like India and Hong Kong.	Training costs can accumulate quickly, deterring adoption of IR4.0 technologies.

Table 2 Summary of strength and weaknesses of adoption IR4.0 in the construction sector (cont')

Strength	**Weakness**
Emphasis on sustainability, aesthetics, and high-end market segments counters the historical perception of prefabricated housing as low-quality.	High requirements and lack of knowledge in handling IR4.0 technologies present barriers to adoption.
New entrants and first movers disrupt the market, driving change and innovation in the industry.	Adoption of IR4.0 can disrupt workplace culture, management structures, and productivity.
The use of advanced building materials reduces demand for construction site facilities, improves safety, and lowers labour expenses.	Integration of IR4.0 technologies requires ongoing monitoring and support to ensure continual improvement.
Standardisation and modularisation lead to cost savings, fewer interface issues, and improved output predictability.	Users may be unwilling to embrace new technologies without immediate support and assistance.
Integration of Building Information Modelling (BIM) and Augmented Reality (AR) enhances construction efficiency, management, and data distribution.	Adoption of IR4.0 has broad repercussions for the construction industry, companies, the environment, and the public, requiring careful consideration and strategic planning.
Data analytics optimises risk management, project management, and cost savings in the construction industry.	Stakeholders must overcome various hurdles to successfully transition to Industry Revolution 4.0 and gain a competitive advantage.

3.3 Opportunities (O) for the Adoption of IR4.0 in Construction Sector

Looking from another perspective, the opportunities identified in the SWOT framework are directly derived from the PESTLE analysis. The political (P) factor suggests that local construction enterprises can enhance their global competitiveness by leveraging cutting-edge technologies to achieve the highest product quality and outcomes. Innovative technology and concepts reduce both construction and product delivery times in economic terms (E). Technology would also lead to cost savings on things like labour and materials, resulting in greater profits. From a social perspective, the critical factor is enhancing the company's image. The digital revolution in the industry would create a more innovative working environment than currently exists, fostering increased partnerships with partners and engaging consumers. IR4.0 enhances safety by training workers or minimising risks through technology, thereby addressing the potential risk of data leakage. In the Malaysian context, Shafei et al. [50] conducted a fuzzy TOPSIS evaluation of twelve Construction 4.0 technologies identified in the national strategic plan and assessed their contribution to organisational well-being and productivity. Their findings reveal that BIM, IoT, big data & predictive analytics, autonomous construction, and AR/VR are the most influential technologies in enhancing worker well-being, thus reinforcing the social dimension of our PESTLE analysis. Technological Advancement (T), The upgraded system would ensure that there are few to no errors, resulting in better quality assurance. Enough data enables the making of sound judgements, leading to more successful outcomes. Additionally, widespread adoption would require the system to establish a robust regulatory framework, thereby reducing uncertainty and addressing challenges in the legal (L) factor. Finally, stress is a significant concern in the environmental (E) factor, which is as important as sustainability. These advancements can be used to implement various methods for reducing energy consumption. As a result, it is possible to keep track of the amount of garbage produced and avoid polluting the environment. Table 3 presents the external opportunities derived from the PESTLE analysis. Each factor – political, economic, social, technological, legal, and environmental – was reviewed through the lens of recent literature and construction industry practices. The table highlights the potential for IR4.0 technologies to improve global competitiveness, enhance regulatory frameworks, and drive sustainability. These external drivers form the basis for the Opportunities section in the SWOT analysis, aligning macro-environmental forces with industry growth potential. These PESTLE-derived dimensions form the external 'Opportunities' quadrant of the SWOT analysis, offering a macro-level perspective on the enabling factors that support digital transformation in the construction industry.

Table 3 Opportunities in the PESTLE factor

Factor	Opportunity	Explanation
Political (P)	Global Competitiveness	Leveraging advanced technologies to achieve optimal product quality and outcomes, regional construction enterprises can enhance their competitiveness on a global scale.
Economical (E)	Market Dynamics	Save money on things like labour and materials, and it will bring more profits than the cost.
Social (S)	Image Enhancements	The digital transformation in the industry is poised to cultivate a more inventive work environment compared to the present scenario, simultaneously fostering increased collaborations with partners and interactions with consumers.
Technological (T)	Reliable Productivity	An enhanced system would guarantee minimal to no errors, thereby improving quality assurance.
Legal (L)	Safety Enhancement	Well-established regulatory framework, eliminating uncertainty
Environmental (E)	Promote Sustainability	A range of ways to lower energy use can be implemented using these advancements to keep track of the amount of garbage produced and avoid polluting the environment.

3.4 Threat (T) to the Adoption of IR4.0 in Construction Sector

The PESTLE framework, which evaluates external macro-environmental risks affecting IR4.0 adoption, also grounds the 'Threats' identified in the SWOT analysis. The construction support industry, predominantly comprised of small and medium-sized enterprises, faces limitations in investing in technologies with uncertain benefits, as indicated by the political (P) factor. To implement their plans, construction companies often depend on government agencies and authorities for support through funding and collaborative efforts. The economic (E) factor is equally significant, given the high costs associated with adopting innovative technology. The lack of clarity regarding the return on investment complicates matters, and additional hidden costs like training and equipment maintenance further impede implementation efforts. Under the Social (S) component, the adoption of new technologies would have widespread implications for various stakeholders involved in construction projects. However, societal reluctance to embrace new technologies without substantial proof of majority benefits poses a challenge. Security concerns arise as information exchange becomes susceptible to threats, leading to IT security issues related to data privacy and security. In the Technology (T) aspect, standards and practices must be updated to align with the construction environment. The need for advanced capabilities to operate these technologies and the demand for more robust equipment present obstacles to seamless integration into daily practices. The complexity is heightened by a lack of clarity in the division of responsibilities among participants and legal considerations related to faults under the Legal (L) factor. Finally, the Environmental (E) component disrupts common execution techniques due to changes in organisational processes (horizontal, vertical, and end-to-end). Adapting common processes to accommodate these changes and foster growth becomes essential. Table 4 outlines the external threats identified through the PESTLE framework. The challenges include governance limitations, financial uncertainty, cultural resistance, technical vulnerabilities, legal ambiguity, and environmental disruptions. These threats were extracted from key literature and contextualised for the construction domain, especially for SMEs and emerging economies. The insights support the “Threats” quadrant of the SWOT analysis and demonstrate the need for robust policy, investment, and training frameworks to mitigate risks associated with IR4.0 deployment. Together, these challenges form the external 'Threats' in the SWOT matrix, highlighting the systemic and contextual barriers, such as political, economic, legal, and beyond, that must be addressed to realise the full potential of IR4.0 in construction.

Table 4 Threat (T) in the PESTLE factor.

Factor	Challenges	Explanation
Political (P)	Governance	Construction firms would need to depend on support from government agencies and authorities.
Economical (E)	Financial Transparency	The lack of clarity about a return on investment exacerbates the situation.
Social (S)	Cultural Habits	Cultural habits of society are against adopting new technologies unless results are yielded by the majority.
Technological (T)	Technical Challenges and threat risks	Security risk of data and information leakage.
Legal (L)	Ambiguous regulatory	The situation becomes more complicated due to a lack of clarity in defining the responsibilities of each participant.
Environmental (E)	Organisational Processes	Common processes would need to be updated to properly adapt to the new changes and promote growth.

The synthesis of findings from the SWOT and PESTLE frameworks reveals distinct patterns and gaps in the current discourse on IR4.0 in construction. While the global case studies show accelerating adoption of technologies such as BIM, prefabrication, and AI-powered automation, implementation across developing countries, particularly in Southeast Asia, remains fragmented. The literature reviewed suggests that although the benefits of digital transformation are widely recognised, critical barriers such as workforce readiness, integration complexity, and policy inertia persist. Moreover, there is a noticeable lack of longitudinal studies evaluating the long-term effectiveness of IR4.0 interventions. This points to a research gap in post-adoption performance and impact assessments. Additionally, while many studies describe individual technologies, few explore their interdependencies or combined strategic value in real-world construction ecosystems. Addressing these gaps through cross-disciplinary, Malaysia-specific research and evidence-based policymaking is vital to converting theoretical potential into practical outcomes.

3.5 Future Trends in Malaysia

IR4.0 methodologies have been implemented in the construction industry, showcasing significant impacts across various domains. In Malaysia, these efforts are increasingly shaped by policy interventions such as the Construction 4.0 Strategic Plan, which aims to align local practices with international standards in BIM, automation, and data integration. Abdul-Samad et al. [51] conducted a survey among licensed Grade 5–7 contractors in Malaysia to assess their level of understanding and organisational readiness for IR 4.0. The results indicate moderate awareness and capability in knowledge, technology adoption, and operations management, underscoring a growing yet uneven engagement across the sector. As noted by previous researchers, the concept of Construction 4.0 continues to evolve, drawing inspiration from the principles of its predecessors in the realm of the Fourth Industrial Revolution.

However, for successful implementation, all stakeholders must overcome the emerging challenges. While the social element is recognised as the primary factor influencing successful implementation, the interrelated nature of other contributing variables implies that they should be addressed concurrently. The construction sector requires a strategic plan at various levels to systematically transition towards IR4.0. The construction sector's transformation framework lays out a comprehensive strategy. Based on responsibility, the framework brings together the many regions and levels of operation. To begin with, changes are dependent on individual enterprises' creativity, the application of fresh technology and procedures, business model development, and changes to company culture and association. A single, isolated action is insufficient. Several difficulties and impediments should be handled jointly in the construction sector, which is largely fragmented and horizontal, so that the industry is held accountable. It asks for the creation of new cooperative systems or the improvement of existing ones. Finally, governments, in their multiple roles as decision-makers, regulators, and clients, have a significant role to play. Not only will there be staff and computer interaction in smart construction projects, but also thing-to-thing contact to improve outcomes to meet stakeholders' needs. Three types of combinations must be considered: "horizontal, vertical, and end-to-end." Horizontal interacting interests in a peer group of value-creation systems, including integration of diverse mediators such as business associates and clients, whereas vertical interacting interests in smart building schemes are alternatives to traditional static construction methods. The goal of end-to-end integration is to improve product design, construction, and user experience along the whole value chain.

Stakeholders can use digitisation as a tool to improve efficiency. Although other businesses have previously benefited along the entire value chain, the construction industry continues to lag. Only a small percentage of stakeholders have adopted digitisation as a means of improving their performance and productivity. Consumer attitudes toward prefab homes are beginning to shift, especially when new, more diversified material options improve prefab structures' visual appeal. Perhaps most importantly, we're seeing a shift in mindset among construction CEOs, as many acknowledge the arrival of technology-based disruptors and realise it's time to reposition themselves. After decades of relatively sluggish transformation, an at-scale transition to modularisation, coupled with digitisation, appears to be on the verge of disrupting the construction sector and the wider ecosystem. To guarantee that they gain rather than risk being left behind, all participants should review the trend and its influence, as well as their strategic choices.

The Malaysian construction industry shrank by 60% between 2016 and 2018, a statistic that is expected to worsen as a result of the continuing pandemic's constraints on all sectors, according to the Department of Statistics, Malaysia, in January 2022. It was also predicted that the global construction industry's market size would fall this year before rising the next year, reaching a market size of US$11,496.7 billion [47]. The COVID-19 pandemic accelerated the digitisation of construction companies, compelling them to adopt digital technologies despite the industry's long-standing position as one of the least digitised sectors and its reputation for resisting technological change. This compelled adoption kept projects on track and highlighted the positive impact these technologies can have. This was especially noticeable in terms of production and efficiency. When many expected productivities to diminish, the usage of these formerly frowned-upon tools provided an entirely new and exciting style of working. According to IBM, following the pandemic, 62 per cent of leaders have given digital transformation a "high or very high priority" in 2022, compared to only 17% in 2018 [48]. Anticipated economic recovery is projected to contribute to the rise in demand for antibacterial building materials and 21st-century technology (IR4.0). The digitisation of relevant data holds the potential to facilitate prompt responses to problem-solving and collaborative business environments. This transformation will impact not only the conception, construction, and maintenance of physical structures but also their utilisation.

While the construction industry serves as a crucial economic driver, similar to its impact on the manufacturing sector, the adoption of IR4.0 has the potential to enhance its efficiency. The success of IR4.0 has led to the creation and advancement of other technologies. Evidence suggests that the construction industry significantly contributes more than its share to the development and promotion of digital technologies.

There is no doubt that the construction environment has been rocked by this "new normal". Construction stakeholders acknowledge the need for digital solutions to preserve productivity and help our business thrive now more than ever. With no signs of digital adoption stopping, today is more important than ever to continue our joint progress. We must make certain that we do not miss out on the benefits of IR4.0. Stakeholders from government, academia, and business will all play a key role in solving this challenge, particularly in terms of preparing the next generation for future construction jobs in a post-COVID-19 world. The trends and insights derived from the SWOT and PESTLE analyses point to the urgency of a comprehensive and coordinated transformation strategy. These findings align closely with the study's objectives by not only emphasising the advantages of IR4.0 adoption but also identifying the structural adjustments and policy interventions necessary for its effective implementation within Malaysia's construction sector. In this context, Malaysia emerges as a strategic testbed, where national policy aspirations must be balanced against on-the-ground realities, particularly among small and medium-sized enterprises (SMEs) that face distinct challenges in digital transformation.

4.0 CONCLUSION

The current integration of IR4.0 in the construction industry is driven by the development and implementation of various technologies that have significantly contributed to its success. Over the past three years, the adoption of digital approaches in design and construction has matured, becoming standard practice for many organisations. The use of these technologies streamlines work processes, leading to higher productivity, and the transition from traditional methods is only a matter of time.

BIM has been at the forefront of digitalising the building industry in recent years. The implementation of IR4.0 technologies has revealed a performance gap, highlighting the substantial disparity between how building designs are assessed for compliance in the virtual world and how structures function in the real world. The tangible results are evident when comparing the GDP of a country before and after the implementation of IR4.0 in the construction industry.

Looking ahead to the future trends in the Malaysian construction industry, it will require collaborative efforts from industry stakeholders, government bodies, and academic institutions to address the challenges. It is crucial to reassess the training needed for the next generation to meet future job requirements. The Ministry of Works (Kementerian Kerja Raya – KKR), through CIDB, is collaborating with various stakeholders in the construction industry to develop a Construction Strategy Plan 4.0 (2021–2050) to guide the industry through these transformative changes.

In summary, despite the challenges, the implementation of IR4.0 in the construction sector will enhance its performance to align with counterparts in the manufacturing and automotive industries. Embracing IR4.0 is undoubtedly the future trajectory, and its integration into the construction site is inevitable. Future research should consider incorporating Malaysian-specific case studies that demonstrate the practical implementation of IR4.0 technologies in construction projects. Such empirical insights would provide a more grounded understanding of local adoption patterns, industry challenges, and technological readiness. Additionally, a dedicated policy analysis is recommended to explore how national initiatives, such as the CIDB Construction 4.0 Strategic Plan, can be translated into actionable strategies for stakeholders across the public and private sectors. This includes identifying mechanisms to support small and medium enterprises (SMEs), incentivise technology adoption, and strengthen industry-academia collaborations to bridge the current skill gap in digital construction.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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References

[1] Yousif, O. S., Zakaria, R., Wahi, N., Aminudin, E., Tharim, A. H., Jawa Gara, A., Ismail, N. (2022). Monitoring The Construction Industry Towards a Construction Revolution 4.0. International Journal of Sustainable Development and Planning, 17(2), 633–641. https://doi.org/10.18280/ijsdp.170228

[2] Bielenberg, A. (2009). Ireland and The Industrial Revolution: The Impact of The Industrial Revolution on Irish Industry, 1801–1922. Routledge. https://doi.org/10.4324/9780203879337

[3] He, Q., & Han, L. (2021). Research on Adaptive Repair Technology of 3D Printing Based on convolutional Neural Networks. In Proceedings of the IEEE 21st International Conference on Communication Technology (ICCT) (pp 1198-1201). Tianjin, China. https://doi.org/10.1109/ICCT52962.2021.9657912.

[4] Javaid, M., Haleem, A., Singh, R. P., & Suman, R. (2023). An Integrated Outlook of Cyber–Physical Systems for Industry 4.0: Topical Practices, Architecture, and Applications. Green Technologies and Sustainability, 1(1), Article 100001. https://doi.org/10.1016/j.grets.2022.100001

[5] Bilal, M., Oyedele, L. O., Akinade, O. O., Ajayi, S. O., Alaka, H. A., Owolabi, H. A., Qadir, J., Pasha, M., & Bello, S. A. (2016). Big Data Architecture for Construction Waste Analytics (CWA): A Conceptual Framework. Journal of Building Engineering, 6, 144–156. https://doi.org/10.1016/j.jobe.2016.03.002

[6] Medeiros, J. S., & Melo, R. S. (2022). Lessons learned from adopting modular construction in Brazil: A Startup Journey. In Proceedings of the 2022 Modular and Offsite Construction Summit. Edmonton, AB, Canada. https://doi.org/10.29173/mocs265

[7] Generalova, E. M., Generalov, V. P., & Kuznetsova, A. A. (2016). Modular Buildings in Modern Construction. Procedia Engineering, 153, 167–172. https://doi.org/10.1016/j.proeng.2016.08.098

[8] Amin, M. N., Ahmad, W., Khan, K., & Ahmad, A. (2022). A Comprehensive Review of Types, Properties, Treatment Methods and Application of Plant Fibers in Construction and Building Materials. Materials, 15(12), Article 4362. https://doi.org/10.3390/ma15124362

[9] Sharma, R., Jang, J. G., & Hu, J. W. (2022). Phase-Change Materials in Concrete: Opportunities and Challenges for Sustainable Construction. Materials, 15(1), Article 335. https://doi.org/10.3390/ma15010335

[10] Cui, K., Chang, J., Feo, L., Chow, C. L., & Lau, D. (2022). Developments and Applications of Carbon Nanotube Reinforced Cement-Based Composites as Functional Building Materials. Frontiers in Materials, 9, Article 861646. https://doi.org/10.3389/fmats.2022.861646

[11] Li, W., Zhang, Z., & Zhou, J. (2022). Preparation of Building Materials from Bayer Red Mud With Magnesium Cement. Construction and Building Materials, 323, Article 126507. https://doi.org/10.1016/j.conbuildmat.2022.126507

[12] Khajavi, S. H., Tetik, M., Mohite, A. M., Peltokorpi, A., Li, M., Weng, Y., & Holmström, J. (2021). Additive Manufacturing in The Construction Industry: The Comparative Competitiveness of 3D Concrete Printing. Applied Sciences, 11(9), Article 3865. https://doi.org/10.3390/app11093865

[13] Shakor, P., Chu, S. H., Puzatova, A. V., & Dini, E. (2022). Review of Binder Jetting 3D Printing in The Construction Industry. Progress in Additive Manufacturing, 7(3), 643–669. https://doi.org/10.1007/s40964-021-00252-9

[14] Parisi, F., Sangiorgio, V., Parisi, N., Mangini, A. M., Fanti, M. P., & Adam, J. M. (2023). A New Concept for Large Additive Manufacturing in Construction: Tower Crane-Based 3D Printing Controlled by Deep Reinforcement Learning. Construction Innovation, 24(1), 8–32. https://doi.org/10.1108/CI-10-2022-0278

[15] Valencia, N. (2017). World's First 3D Printed Bridge Opens in Spain. ArchDaily.

[16] Feng, C., Fredricks, N., & Kamat, V. R. (2013). Human–Robot Integration for Pose Estimation and Semi-Autonomous Navigation on Unstructured Construction Sites. In Proceedings of the 30th International Symposium on Automation and Robotics in Construction (ISARC). Montreal, Canada. 1317-1325. https://doi.org/10.22260/ISARC2013/0148

[17] Haschke, T., Hüsing, M., & Corves, B. (2022). Bots2ReC – Analysis of Key Findings for the Application Development of Semi-Autonomous Asbestos Removal. International Journal of Automation & Digital Transformation, 1(1), 4–12. https://doi.org/10.54878/IJADT.166

[18] Lee, D., & Spong, M. W. (2006). Semi-Autonomous Teleoperation of Multiple Cooperative Robots for Human–Robot Lunar Exploration. In To Boldly Go Where No Human-Robot Team Has Gone Before: Papers from the 2006 AAAI Spring Symposium (Technical Report SS-06-07). Stanford, CA, USA.

[19] Rankohi, S., & Waugh, L. (2013). Review And Analysis of Augmented Reality Literature for The Construction Industry. Visualization in Engineering, 1(1), Article 9. https://doi.org/10.1186/2213-7459-1-9

[20] Monla, Z., Assila, A., Beladjine, D., & Zghal, M. (2023). Maturity Evaluation Methods for BIM-Based AR/VR in the Construction Industry: A Literature Review. IEEE Access, 11, 101134–101154. https://doi.org/10.1109/ACCESS.2023.3281265

[21] Piroozfar, A., Farr, E. R. P., Essa, A., Boseley, S., & Jin, R. (2018). Augmented Reality (AR) and Virtual Reality (VR) in The Construction Industry: An Experiential Development Workflow. In Proceedings of The Tenth International Conference on Construction in the 21st Century (CITC-10). Colombo, Sri Lanka

[22] Tan, Y., Xu, W., Li, S., & Chen, K. (2022). Augmented and Virtual Reality (AR/VR) for Education and Training in the AEC Industry: A Systematic Review of Research and Applications. Buildings, 12(10), Article 1529. https://doi.org/10.3390/buildings12101529

[23] Guray, T. S., & Kismet, B. (2022). VR and AR in Construction Management Research: Bibliometric and Descriptive Analyses. Smart and Sustainable Built Environment, 12(3), 635–659. https://doi.org/10.1108/SASBE-01-2022-0015

[24] Kim, Y., Lee, J., Lee, E., & Lee, J. (2020). Application of natural language processing (NLP) and text-mining of big data to EPC bid and contract documents. In Proceedings of the 2020 6th Conference on Data Science and Machine Learning Applications (CDMA) Riyadh, Saudi Arabia. 123-128. https://doi.org/10.1109/CDMA47397.2020.00027

[25] Yuan, X., Chen, Y., Fan, H., He, W., & Ming, X. G. (2019). Collaborative Construction Industry Integrated Management Service System Framework Based on Big Data. In Proceedings of the 2019 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM) Macao, China. 1521-1525. https://doi.org/10.1109/IEEM44572.2019.8978624

[26] Choi, S., Lee, E., & Kim, J. (2021). The Engineering Machine-Learning Automation Platform (EMAP): A Big-Data-Driven AI Tool for Contractors' Sustainable Management Solutions for Plant Projects. Sustainability, 13(18), Article 10384. https://doi.org/10.3390/su131810384
[27] Nagy, J., Oláh, J., Erdei, E., Máté, D., & Popp, J. (2018). The Role and Impact of Industry 4.0 and the Internet of Things on the Business Strategy of the Value Chain: The Csse of Hungary. Sustainability, 10(10), Article 3491. https://doi.org/10.3390/su10103491
[28] Zhang, M., Cao, T., & Zhao, X. (2017). Applying Sensor-Based Technology to Improve Construction Safety Management. Sensors, 17(8), Article 1841. https://doi.org/10.3390/s17081841
[29] Hustad, E., & Olsen, D. H. (2021). Creating a Sustainable Digital Infrastructure: The Role of Service-Oriented Architecture. Procedia Computer Science, 181, 597–604. https://doi.org/10.1016/j.procs.2021.01.210
[30] Rashid, A., & Chaturvedi, A. (2019). Cloud Computing Characteristics and Services: A Brief Review. International Journal of Computer Sciences and Engineering, 7(2), 421–426. https://doi.org/10.26438/ijcse/v7i2.421426
[31] Kiriiak, N. (2021). Development and Implementation of Technical Decision for Digital Support of Construction Using Photogrammetry Methods. Nuclear Engineering and Design, 381, Article 111366. https://doi.org/10.1016/j.nucengdes.2021.111366
[32] Safa, M., Nahangi, M., Shahi, A., & Haas, C. T. (2013). An Integrated Quality Management System for Piping Fabrication Using 3D Laser Scanning and Photogrammetry. In Proceedings of the 30th ISARC. Montréal, Canada. https://doi.org/10.22260/ISARC2013/0073
[33] Kudela, P., Palčák, M., Zábovská, K., & Bučko, B. (2020). Integration of Photogrammetry Within Laser Scanning Approach. In 43rd International Convention on Information, Communication and Electronic Technology (MIPRO). 1691-1694. https://doi.org/10.23919/MIPRO48935.2020.9245297
[34] Dikbas, A., & Scherer, R. (2004). Virtual Building Environments (VBE): Applying Information Modeling to Buildings. CRC Press. https://doi.org/10.1201/9780203023426-16
[35] McAuley, B., Hore, A., & West, R. (2017). BICP Irish BIM Study. Irish Building Magazine, 1, 77–79. https://doi.org/10.21427/sfxa-rs67
[36] Wu, K., Soto, B. G., Adey, B. T., & Zhang, F. (2020). BIM-Based Estimation of Vertical Transportation Demands During the Construction of High-Rise Buildings. Automation in Construction, 110, Article 102985. https://doi.org/10.1016/j.autcon.2019.102985
[37] Vignali, V., Acerra, E. M., Lantieri, C., Vincenzo, D. F., Piacentini, G., & Pancaldi, S. (2021). Building Information Modelling (BIM) application for an existing road infrastructure. Automation in Construction, 128, Article 103752. https://doi.org/10.1016/j.autcon.2021.103752
[38] Li, J., Afsari, K., Li, N., Peng, J., Wu, Z., & Cui, H. (2020). A Review Presenting Building Information Modeling Education and Research in China. Journal of Cleaner Production, 259, Article 120885. https://doi.org/10.1016/j.jclepro.2020.120885
[39] Taher, G. (2021). Industrial Revolution 4.0 in the construction industry: Challenges and opportunities. Management Studies and Economic Systems, 6(3–4), 109–127. https://doi.org/10.12816/0060000
[40] Jones, N. (2016). A century of prototypes: A capsule history of modular architecture. The Possible.
[41] BBC. (2014). How Dutch team is 3D-printing a full-sized house. BBC News.
[42] Smisek, P. (2018). This rover carries materials on site. The B1M.
[43] Zhang, Z., & Pan, W. (2021). Virtual Reality Supported Interactive Tower Crane Layout Planning For High-Rise Modular Integrated Construction. Automation in Construction, 130, Article 103854. https://doi.org/10.1016/j.autcon.2021.103854
[44] Young, N. W., Jr., Jones, S., & Bernstein, H. M. (2008). Building Information Modeling: Transforming Design and Construction to Achieve Greater Industry Productivity. McGraw-Hill.
[45] Azhar, S. (2011). Building Information Modeling (BIM): Trends, Benefits, Risks, and Challenges for the AEC industry. Leadership and Management in Engineering, 11(3), 241–252. https://doi.org/10.1061/(ASCE)LM.1943-5630.0000127
[46] Neugebauer, R., Hippmann, S., Leis, M., & Landherr, M. (2016). Industries 4.0—From the Perspective of Applied Research. Procedia CIRP, 57, 2–7. https://doi.org/10.1016/j.procir.2016.11.002
[47] Adeleke, A. Q. (2020). Industrial Revolution 4.0 Can Help Boost the Construction Industry. New Straits Times.
[48] Bieck, C., & Marshall, A. (2022). How to invest now to expedite COVID-19 recovery: Redirecting resources for enterprise transformation. IBM Institute for Business Value.
[49] Khudzari, F., Radzi, A. R., & Rahman, R. A. (2024). Emerging Technologies Adoption in The Malaysian Construction Industry: A Systematic Review. Malaysian Construction Research Journal, 42(1), 57–75.
[50] Shafei, H., Rahman, R. A., Lee, Y. S., & Che, C. (2024). Implications of Construction 4.0 Technologies to Enhancing Well-Being: A Fuzzy TOPSIS Evaluation. Construction Innovation. Advance Online Publication. https://doi.org/10.1108/CI-08-2023-0213

[51] Abdul-Samad, Z., Lim, L. X., Alaloul, W. S., & Salleh, H. (2024). Towards Industrial Revolution (IR) 4.0 in the construction industry: Readiness of contractors. Results in Engineering, 22, 102321. https://doi.org/10.1016/j.rineng.2024.102321

[52] Chan, S., Chai, C., Lim, C. B., Ekambaram, P., Ghani, M. K. B., & Lee, C. (2023). Navigating the path to Construction 4.0: Policies, challenges, and strategies in Malaysian construction industry. GATR Journal of Business and Economics Review, 8(3), 89–103. https://doi.org/10.35609/jber.2023.8.3(3)